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Mars Pathfinder Active Heat Rejection System: Successful Flight Demonstration of a Mechanically Pumped Cooling Loop

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ABSTRACT

One of the new technologies successfully demonstrated on the recent Mars Pathfinder mission was the active Heat Rejection System (HRS). This system consisted of a mechanically pumped cooling loop, which actively controlled the temperatures of the various parts of the spacecraft. A single phase Refrigerant 11 liquid was mechanically circulated through the lander and cruise electronics box heat exchangers. This liquid transferred the excess heat to an external radiator on the cruise stage. This is the first time in unmanned spacecraft history that an active heat rejection system of this type has been used on a long duration spacecraft mission. Pathfinder was launched in December 1996 and landed on the Martian surface on July 4, 1997. The system functioned flawlessly during the entire seven months of flight from Earth to Mars.

A life test set up of the cooling loop was used to verify the life of the system. The life test system was run for over 14, 000 hours before complete examination of the components used in the life test was made. Some of the components used in the system were tested in the life test set up. The results from the life test loop indicate no major issues that would hinder the pumped loop operation for many more years.

INTRODUCTION

The Mars Pathfinder Spacecraft successfully landed on the Martian surface on July 4, 1997 after a seven-month cruise in space. For the next three months, it sent valuable data collected by the microrover to Earth. One of the key technologies that enabled the mission to succeed was an active heat rejection system (HRS) used to cool the electronics on the spacecraft. This HRS consisted of a mechanically pumped single phase cooling system for cooling the electronics and other spacecraft components on the Mars Pathfinder spacecraft. It was the first time an active cooling system of this type was used in a deep space mission in the U.S. history.

In terms of thermal control design, the Mars Pathfinder spacecraft could be considered as consisting of three separate parts. The first part is the Cruise Stage consisting of power, propulsion, and navigation equipment needed to take the spacecraft to Mars. The second part is the entry, descent, and landing stage consisting of an aeroshell and deceleration module to help the lander safely enter the Martian environment and land on the surface. The third part is the Lander that houses the instruments including the Sojourner microrover. A detailed description of the mission is given in Reference 1.

The mechanically pumped loop was developed for the Mars Pathfinder mission because of the unique requirements and constraints posed by the mission. A description of the reasons for selecting the active cooling loop is given in References 2 and 3. A schematic of the spacecraft is shown in Figure 1. The same communication and data analysis electronics are used both during cruise and landed operations. This equipment is located on the base petal of the lander and is completely enclosed in very high performance insulation to conserve heat during the cold Martian nights (as cold as -80 C). During cruise, the same equipment is operated continuously at about 90 Watts of power to communicate with ground. Because of 1) power level, 2) high temperature (15 C near earth) outside the insulated enclosure, and 3) additional insulation from the stowed airbags, it is very difficult to passively dissipate the heat. These conditions in the spacecraft configuration necessitated a heat rejection system (HRS) for Pathfinder. The main functions of HRS were to transfer heat from the lander during cruise and minimize heat leak from the enclosure during Martian nights.

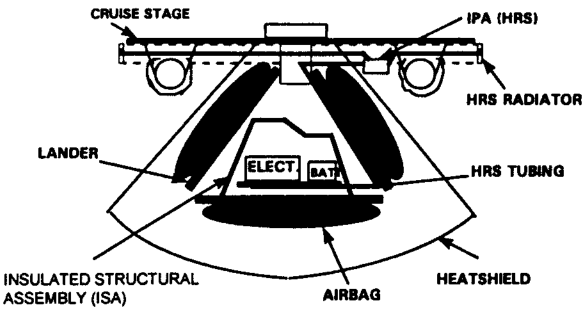

Figure 1. Mars Pathfinder Thermal Control Configuration

Because of the short schedule available for the implementation of the system on the spacecraft, several new approaches were used for the design, qualification and verification of the system. The engineering and flight development were done in parallel. A description of this is given in Reference 4.

Some of the interim results from the ground and flight test data were presented earlier in Reference 2. In this paper, the final data from the flight system up landing time are presented. Also, the data from the 14,000 hours of life test pump operation is presented.

THE ACTIVE HEAT REJECTION SYSTEM

THE MARS PATHFINDER active Heat Rejection System was designed to keep the key spacecraft components within the allowable temperature range. This was accomplished by using a mechanically pumped single-phase liquid loop to transfer excess heat from the components inside the spacecraft to an external radiator. A description of this system and how it was selected after various thermal control options were examined is given in References 2 to 5.

The Pathfinder mission requirements on the HRS were as follows:

1) Transfer 90 to 180 Watts of heat to radiator
2) Maintain the working fluid in single phase in the temperature range of -100 to +70 C with the vapor pressure of less than 100 psia.
3) Maintain a total HRS mass of less than 18 kg including working fluid
4) Keep the maximum power consumption to less than 10 Watts

A schematic of this system is shown in Figure 2. The key components of the HRS are the following:

1. Integrated Pump Assembly (IPA)
2. Radiator
3. HRS tubing
4. Freon-11 working fluid
5. Refrigerant 11 vent system
6. Electronic shelf

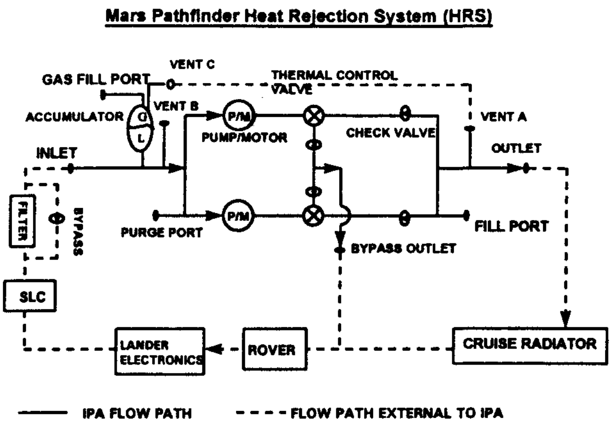

Figure 2. Mars pathfinder Heat Rejection System

The IPA, which is a major element of the HRS, circulates and controls the flow of refrigerant 11 in the mechanical cooling loop. It consists of mechanical centrifugal pumps, an accumulator, thermal control valves, and control electronics. The specifications, design, and implementation of the IPA in the Pathfinder HRS are described in Reference 4.

The details of the design and fabrication of the cooling loop are given in References 5. The description of the selection of the working fluid, design of the venting system, verification of the thermal-hydraulic performance of the system is all given in the above reference. As part of verifying the design, several engineering tests were conducted on the component level. These tests involved thermal-hydraulic performance tests, leak tests on mechanical joints, and material compatibility tests on all the materials used in the HRS system.

In the development of the HRS, several new technologies were developed. The key new technologies developed and used in the system are the use of Refrigerant 11 as a single-phase working fluid and a wax-actuated thermal control valve to control the fluid temperature in the loop. A description of the thermal control valve is given in Reference 4.

THE FLIGHT COOLING SYSTEM was tested at two levels – assembly level and the spacecraft level. At the assembly level, tests were done to verify the performance of the subassemblies such as the Integrated Pump Assembly. Here the hydraulic, electrical, and thermal performance of the IPA was tested. In addition, the IPA was subjected to the thermal vacuum, random and sinusoidal vibration, and Electro Magnetic Interference and Compatibility (EMI & EMC) tests to qualify it for the flight.

At the spacecraft system level, the whole system went through a series of system level tests. These tests consisted of vibration, EMI & EMC, and system thermal vacuum tests. The end-to-end performance of the HRS was tested during the thermal vacuum test.

LIFE TEST SET UP

A LIFE TEST COOLING LOOP was built and subjected to long term operation to verify the reliability of the various components of the flight HRS. A schematic of the set up is shown in Figure 3. The life test simulated the long-term operation of the pump assembly, particle filter, and the rest of the HRS (aluminum and stainless steel tubes, Teflon tubing, accumulator, check valves etc). A detailed description of this set up is given in Reference 3.

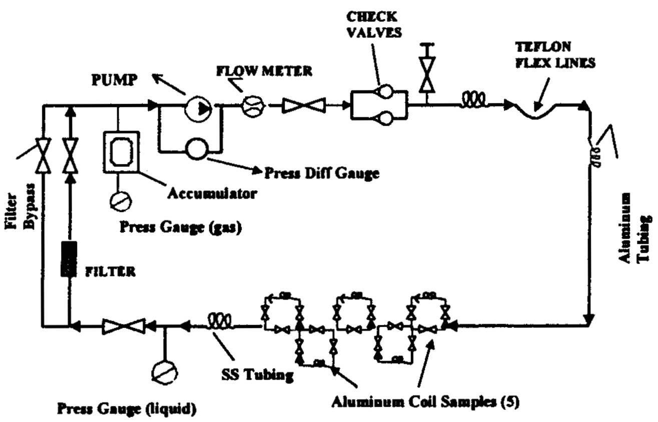

Figure 3. Life Test Schematic

The life test was also used to investigate and measure the long term corrosion of the HRS tubing material (aluminum and Stainless steel) in a flowing environment with all the materials and components used in the flight system. Samples of tubing and the working fluid were taken out and tested periodically. Further, the long-term leak rates of the HRS were monitored during the life test.

The life test set up had operated continuously for 8,000 hours before the actual launching of the Mars Pathfinder spacecraft in December 1996. The results from the operation of the life test are described in Reference 3. The test results showed no evidence of the corrosion after seven-month operation of the loop. The leak rate of the fluid from the system was minimal; it was much lower than the leak rate that was allowed in the flight system.

The performance of the life test loop was monitored continuously. In Figure 4, the performance is shown for the first sixteen months of the loop. It shows flow rate, pressure rise, and electric power consumption of the pump.

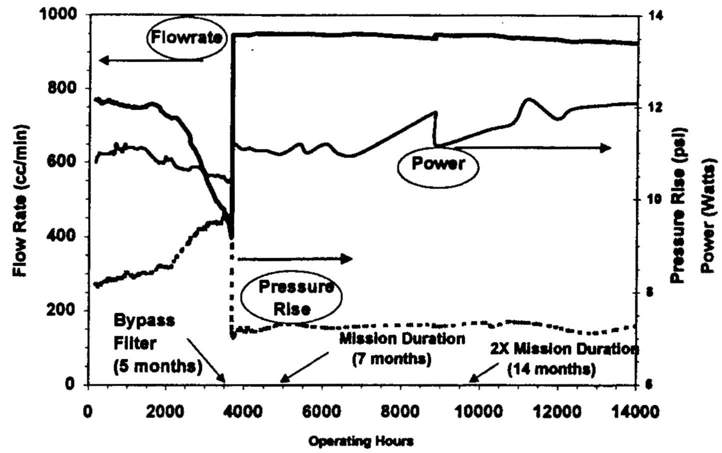

Figure 4. Life Test Performance

One of the lessons learned from the life test loop was that the back up pump needed to be turned on regularly in order to flush any particles that might settle in the pump bearings. During the life test operation, it was noticed that the particles tend to settle in the bearings and impeller area if the pump is stopped for an extended period of over four weeks. Based on this information, the backup pump in the flight system was turned on for an hour once every month.

After the successful landing of the Mars Pathfinder on Mars in July 1997, the life test system was stopped. By this time the life test pump had continuously operated for over 14,000 hours. The tubing and the fluid were investigated for the corrosion and other particulate material. Of particular importance was the particulate that had clogged the filter during the life test.

The chemical analysis showed no evidence of corrosion in the aluminum tubing. The particulate in the fluid sample was found to consist of sizes in the 1 to 40 micron range. The large particles were mostly silica, fibers, and some metallic particles. The smaller particles were mostly chromium, iron, and aluminum. The moisture levels were less than 5 PPM compared to about 17 PPM found in sample taken at 5-month period.

.The organic residue found in the Refrigerant 11 was similar to the material used in the thread of the in-line filter. Most of the particles generated in the life test loop were found to be due to the materials used in the life test set up. Except for the Teflon tubing and the Chromium used in the pump, none of the other materials were used in the flight system.

The scanning electron microscopy done on the aluminum tubing indicated that the prominent mode of corrosion of the aluminum tubing is the physical erosion by the chromium particles being formed at the pump.

FLIGHT SYSTEM DATA

THE HRS PERFORMANCE was continuously monitored during the entire cruise to Mars. The HRS was first activated on the launch pad about two hours before launch. Both the pumps were turned on and the functioning of the system was verified by the current draw of the pumps. The temperature of the electronic equipment shelf and the radiator were also monitored to make sure the working fluid was flowing freely. About four hours after launch, the backup pump was turned off and only the primary pump was on during the rest of the seven-month cruise to Mars. The back up pump was turned on once a month for an hour to ensure that no particulate accumulated in the idle pump.

The performance of the HRS system during the initial periods was very close to the performance predicted and verified during the system level thermal vacuum test. The equipment shelf temperatures was maintained at around +5 C, whereas the radiator temperature was around –4 C. At these radiator temperatures, all the cooling fluid coming out of the equipment shelf was above 0 C and the thermal control valve is completely open. All the fluid flows through the radiator without any bypass. A temperature profile of the equipment shelf and the radiator is shown in Figure 5 for one-hour duration on January 28, 1997.

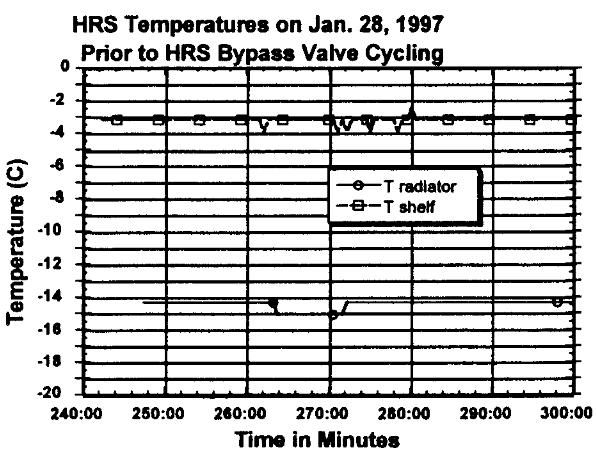

Figure 5. HRS Temperature during Initial Flight

The radiator temperature was a function of the distance from the sun and the sun angle on the spacecraft. This temperature dropped as the spacecraft cruised away from the earth towards Mars. The temperature dropped from –4 C immediately after launch to below –12 C after forty-five days into the cruise. At this time, the fluid temperature coming out of the shelf was below 0 C. As this fluid enters the IPA, the wax actuated thermal valve would open the bypass port and part of the fluid would bypass the radiator. This bypass was designed to keep the electronic shelf above – 7 C irrespective of what the radiator temperature was.

In Figure 6, the temperatures of the equipment shelf and the radiator are shown for day when the radiator bypass had just started. In this case, the shelf was maintained between – 4 and –2 C while the radiator temperature varied between –16 and –14 C. The small fluctuation in the radiator and the shelf temperature was due to the valve actuator continuously trying to adjust to the fluid temperature. This was observed and investigated during the system thermal vacuum test. The fluctuation was attributed to an under-damped flow system and was considered harmless to the system.

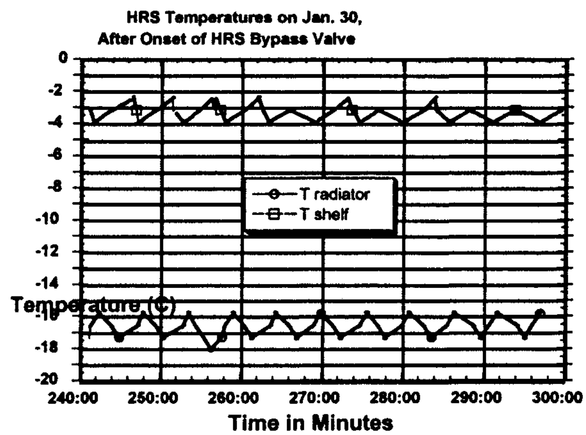

Figure 6. HRS Temperatures during Later part Flight

As the spacecraft neared Mars, the radiator temperature gradually dropped down to – 70 C. However, the equipment shelf maintained its temperature at around -4 C. The radiator and the electronic shelf temperatures during the complete mission are shown in Figure 7.

The HRS system was designed to vent all the working fluid just prior to entering the Martian environment. About 90 minutes before the entry, the vent system was activated by the opening of a pyro-valve that connects the high-pressure gas side of the accumulator to the liquid. The liquid is in turn vented to space via a nozzle, which is opened to space via another Pyro valve (Reference 5). This event occurred on July 4 1997 around 8 AM Pacific Standard Time. The spacecraft navigational data received by the ground controllers indicated that the nutation due to venting was less than two degrees and did not affect the spacecraft course to the Martian landing site.

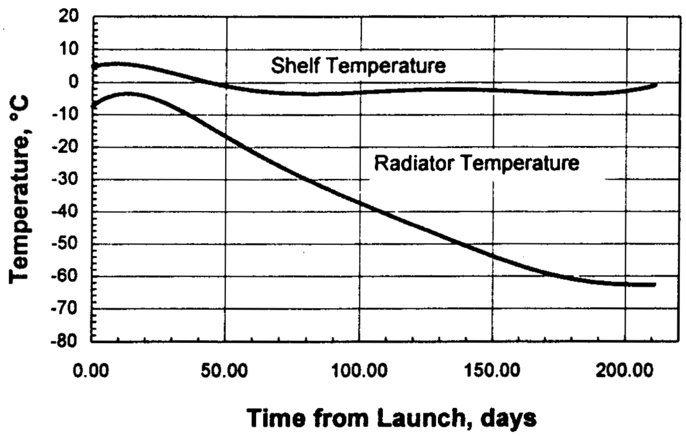

Figure 7. Radiator and electronic Shelf Temperature during the Entire Flight to Mars

CONCLUSIONS

An active heat rejection system consisting of a mechanically pumped single-phase liquid was designed and developed for the Mars Pathfinder mission. The unique requirements of the mission necessitated the use of the pumped loop system for the thermal control of the spacecraft during the cruise to Mars. Because this was the first time that such a system was designed and flown, several new technologies were developed to make the loop successful. These technologies include the use of refrigerant 11 as a cooling fluid and a wax actuated thermal control valve to bypass the flow. The Refrigerant 11 system allows the operation of the system down –110 C. It was the first time that a mechanically pumped cooling loop was used in a deep space mission.

The successful flight demonstration of the mechanically pumped cooling loop on the Mars Pathfinder mission has shown that an active cooling system can be reliably used in deep space missions. The data from the life test pump combined with the flight data show that the mechanical pumps can be reliably operated for missions lasting over two years. The flexibility provided by the mechanical pump cooling systems in the design, integration, test, and flight operation of spacecraft makes this cooling system an ideal system for not only faster, better, and cheaper missions but also for other missions.

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